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Future-State Decisionmaking Under the
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This report asserts that a fundamental flaw exists in current systematic combat models--the use of the so-called present-state decisionmaking paradigm. This paradigm is shown not only to be unrealistic but also to rely on hidden models. The report also presents and examines a proposed alternative--the future-state decisionmaking architecture of the Generalized Value System [GVS]. This architecture is shown to be more realistic than present-state decisionmaking, yet practical to implement. The necessary elements of the GVS are discussed in detail, and an example presented. Areas of the proposed GVS architecture which will require additional research are also discussed.

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## Abstract

This report asserts that a fundamental flaw exists in current systemic combat models - the use of the so-called present-state decisionmaking paradigm. This paradigm is shown not only to be unrealistic and but also to rely on hidden models. The report also presents and examines a proposed alternative - the future-state decisionmaking architecture of the Generalized Value System [GVS]. This architecture is shown to be more realistic than present-state decisionmaking, yet practical to implement. The necessary elements of the GVS are discussed in details, and an example presented. Areas of the proposed GVS architecure which will require additional research are also discussed.

## I. Introduction

A primary problem facing military force planners is that they must guess about the scenarios, threat, available systems, political and economic environments and national resolves which will exist at some future time. These force planners commit billions of dollars today to procure weapon systems, based on hypothesized scenarios for ten years hence, with the primary intent of assuring that those systems are sufficiently effective that the postulated situation will not occur.

Combat models play a major, and increasing, role in assisting decisionmaking in this arena of developing doctrine and systems. Force planners have investigated a wide variety of approaches to modelling combat - historical curve fitting (e.g. QJM, [3]); man-in-the-loop (MITL) models (e.g. JANUS, [16]); systemic (no man-in-the-loop) simulations (e.g. VIC, [17]); and analytic models (e.g. COMAN, [1]). Efforts to develop a theory of combat have been attempting for years to make a science out of a very infrequent (at least by the standards of other sciences, which generally can conduct repeatable and controllable experiments) occurrence in history.

There are numerous tradeoffs between systemic and MITL models. MITL models are generally easier to set up and run. Human players can make do with less complete and less extensive data bases than systemic models. Live players are able to react to unforseen or new circumstances with much more flexibility than systemic models, where unforseen situations may require extensive recoding of the program logic. Currently, most systemic models must frequently be stopped and then restarted when, according to the judgement of analysts, the model fails to take reasonable or realistic military actions. Experience has shown that extensive use of this stop/restart capability effectively turns a systemic model into an MITL model, and not necessarily an efficient one at that.

On the other hand, MITL models have at least two significant drawbacks - the difficulty of replicating results and the lack of a clearly defined audit trail regarding critical command and control decisions. This makes the use of such models for force structure analysis extremely difficult, since cause and effect are effectively obscured, and the contribution of a new weapon system or doctrine to the result is almost impossible to separate from the dynamic of the individual players, the "fog" of even simulated battle, or the occurrence of pure luck. For these reasons, despite their difficulties, systemic models seem to be the overwhelming choice for use in force structure analyses.

This report addresses only one aspect of the larger problems outlined above. Specifically, we are concerned with methodologies for modelling decisionmaking in systemic combat simulations. We propose that most current systemic models utilize a fundamentally flawed paradigm for decisionmaking - one which we feel must be altered if these models are to be fully credible and effective, especially at the Division and Corps level. We shall also examine what we feel is a more reasonable, yet achievable, architecture for decisionmaking in systemic models.

## II. Present-State Decisionmaking

Command and control decisionmaking in current systemic models follows what we shall call the *present-state decisionmaking* paradigm. That is, the model makes tactical decisions by examining the values of various attributes of modeled entities and comparing these to certain (generally multiple) test and threshhold values. The logic for these decisions is normally implemented using what are called either tactical decision rules (TDR's) [17], or decision tables, which are in reality little more than "IF ... THEN" constructs. When decisions made in this manner are considered by professional military analysts to be flawed, the normal response is to "fix" the model. These "fixes" may involve either altering the program so as to change the actual logic of the "IF ... THEN" flow, or creating what are often called "external event files," which simply "hard-wire" the model to make a specific, "proper" decision at a specific (model) time. Unfortunately, the use of such "fixes" can cause a near exponential growth in code complexity. In addition, many of these "fixes," especially those implemented via the external event file approach, are highly unstable in that minor variants in the model run (often caused by *other external event file events*) may negate, or fail to trigger the "fix" correctly. Lastly, establishing a clear audit trail of why specific decisions were made becomes increasingly difficult as the number of "fixes" grows.

We believe that most of these difficulties arise because of a single fundamental weakness in this structure. Specifically, the attribute values which are tested against the TDR's are the *current* values, i.e. the values at the same (model) time at which the decision is being made (and probably at which the model will implement it). We claim this is not realistic, and that this manner of use of current values is the primary contributor to most of the "bad" tactical decisions which are made in systemic models. Furthermore, we assert that this methodology effectively includes *other, hidden models*, some of which may have existed only in the analyst/programmer's mind and are therefore neither able to be validated nor subject to the establishment of audit trails. Lastly, we claim that the experiences to date with decisionmaking in systemic models strongly supports the conjecture that the continued use of the present-state paradigm, coupled with the kind of "fixes" described above, is a dead-end approach.

## III. A Model for "Realistic" Decisionmaking

Given what we believe to be the fundamentally flawed nature of the present-state decisionmaking model, we now develop what we contend is a more reasonable architecture for decisionmaking in systemic models. The starting point for our approach is the view that in the "real" world, the current state acts only as a "trigger" to initiate a planning process. As part of this planning, almost all actual decisions are made based, not on the actual current state of the world, but on the perception of the trends (i.e. the *future*) that may be developing. We further claim that this paradigm, which we denote *future-state decisionmaking* to distinguish it from the present-state model, is practical to implement in most systemic models, and that its implementation will greatly enhance the credibility of that class of models. The concept of future-state decisionmaking is a cornerstone of the *Generalized Value System* [GVS] which we are developing as part of the ALARM [6] project, an ongoing, multifaceted effort involving Naval Postgraduate School faculty and students, and contractors.

The development of an architecture for more realistic combat model decisionmaking requires blending both of the above described basic elements of actual decisionmaking - the current situation triggering a decision to initiate a planning process, and then perhaps to initiate an action so as to change a currently anticipated future - with the basic limitations of current computer simulation - most algorithms must be reduced to quantitative computation. Our starting point will be to formally structure a concept which we have lifted from the discipline of control theory - the *state* of an entity. In actual decisionmaking situations, this concept is "fuzzy," but at this point we shall understand it simply to encompass all those attributes of any entity which are known (or felt to be known) by the decision maker. In the more restrictive modelling context this term will represent those relevant attributes of an entity which are in fact represented in the model. The fundamental point about the state, either in the actual or model context, is that it represents attributes of an entity which we are able, either subjectively or objectively, to measure. As perhaps intimated above, we feel changes (or lack of changes) in this state must be viewed primarily as the "trigger" in actual situations for the *start of planning processes.* We further propose the following, greatly simplified, view of that entire processs.

1. The process starts when a either a change (or lack thereof) in the state, or a predetermined time checkpoint causes the decision maker to review the current situation. In certain cases, this review will cause him to conclude that, in some sense, "things are not going well."

2. This recognition, however, does not, in and of itself. generate an instantaneous decision, but only the recognition that some (as yet unspecified) decision *may* have to be made.

3. In the planning or evaluation procedure thus generated, the decisionmaker tries to determine what if any changes he can effect that will "make things better."

4. At the completion of this, the decisionmaker choose the "best" option from among all changes than can "make things better."

While the above may seem absurdly simple, the fact remains that nothing close to this viewpoint is incorporated in current production systemic models. We also believe that another crucial failing in present-state decisionmaking as it is implemented in current systemic combat models is the lack of recognition that, in all but the simplest actual cases, i.e. cases of almost purely automatic reaction ("battle drills"), both the decision and the implementing actions actually occur in the *future*, and frequently *the actions must be initiated a significant time before their desired effects occur.* We feel than any truly credible systemic combat model decisionmaking architecture must capture these aspects.

There are other fundamental consequences of this view that the proper role of the current state is to create, if necessary, the perception that "things are not going well." The first of these is that, for this kind of decisionmaking process to occur, there must first exist some view of how things "should be going," i.e. of how the state should be evolving with time, including how it should be evolving *into the future.* In the military context, this implies, as is almost always the case, the existence of a plan or mission that must be accomplished. But, at the risk of becoming redundant, we again emphasize that this also assumes the ability to consider not only how things are now, but how they appear to be developing into the future. That is, there must exist methodologies or algorithms for projecting the current state into the future, and then comparing that future state to the "plan." (In actual military decisionmaking, this procedure is frequently labeled war gaming.) The key implication from this that current systemic combat models have overlooked is that, in the model context, the proper role of the current state is to serve (in the differential equations sense) as the *initial conditions* for that prediction. But initial conditions presuppose the existence of a differential equation, i.e. a model, that those conditions will apply to. That model, when solved with the appropriate initial conditions, becomes a predictor of the future state of that system. The major weakness in current systemic models that use only present-state decisionmaking is that whatever the model predicts from the current state into the future remains hidden, perhaps to the point of being only a vague notion in the mind of the analyst who developed the program, rather than being explicitly included in the model, and hence being open to examination.

## IV. The Generalized Value System (GVS) - A Systemic Decisionmaking Architecture

To address many of the perceived shortcomings in systemic models, particularly those involved in higher (Corps and Division) level models, and in light of the emergence of the US Army's Airland Battle doctrine, a group of faculty and students at NPS initiated a research project whose goal was the development of new methodologies appropriate for modelling combat under Airland Battle doctrine. This project, already mentioned above, is now titled the Airland Research

Model (ALARM) ([6], [12], [9]), and has three major components:

a. The development and refinement of network-oriented representations and algorithms for modelling of combat processes,

b. The development of a Generalized Value System (GVS) for model decisionmaking which more accurately captures both the effects of the temporal dimension which characterizes decisionmaking at higher command levels and the highly heterogeneous nature of potential targets on Corps-level Airland battlefield, and

c. The development of concepts and structures for implementing high-level systemic combat models in a distributed computer processing environment.

The GVS was originated by Schoenstadt and Parry [10] as part of an effort to develop target selection algorithms which incorporated not only the current threat of a target, but also its potential for threat in the future. This initial concept was then expanded on by Kilmer [7] and others [4] to encompass not only weapon allocation decisions, but force allocation ones as well. The result has been an evolution after which we now mean by the term Generalized Value System a complete systemic decisionmaking architecture, comprised of the following major elements:

(1) For each model entity, an explicitly defined state vector, consisting of quantifiable elements which the model is capable of representing.

(2) A plan or mission. This will be essentially a set of time, distance and force-oriented constraints which a given model decisionmaker will try to satisfy.

(3) A set of explicit algorithms which can produce predicted future states of any given entity, given a present state.

(4) A set of algorithms for deriving a quantitative measure (or measures) of the value of any entity, given the state of that entity.

(5) A set of algorithms for converting a plan or mission and a set of current and future values into decisions.

We shall discuss all of these more extensively in later sections. At this point, we would only reemphasize that we now view the GVS as an architecture - a philosophy of how to more accurately model systemic combat decisions - rather than as a particular set of algorithms. Indeed, as we will point in later discussion, several of the elements listed above are independent of each other, and could be implemented with more than one particular algorithm.

## V. The State Vector

The first fundamental element in our future decisionmaking architecture is the concept of the state vector. (Basically, this concept was introduced in [10].) By the state of a model entity, we mean the quantitative values at a given time of all those entity attributes which will be used in the model decision logic. Of course, in actual military decisionmaking, the state encompasses both quantitative attributes and other qualitative, or subjective attributes, e.g. morale. At this time we do not expect that these attributes would be components of the model state vector, even thought in actual military decisionmaking such factors can be critical. Such is simply a limitation of models, and involves philosophical questions well beyond our discussion here. We also simply feel that there is not any point in a model either representing or predicting the future values of attributes that are not considered in decisionmaking.

The actual number of different attributes composing the state vector and the particular ones chosen are not particularly crucial to the overall architectural concept, and may vary from model to model - their choice is really up to the modeler. In the simplest of cases (as occurs with almost all current models), the state may be nothing more than the number of operational weapons systems owned by that entity. As a goal, a fully realistic model should also include as well attributes that measure at least the four basic combat service support functions of the Airland Battlefield - manning, arming, fueling, and fixing the weapons systems. But the differences between a one-dimensional and a multidimensional state vector are differences only of degree, not of fundamental concept. Practically, until we have more fully tested our ideas in actual systemic models, we believe there is little point in confounding any model tests by using more than a one-dimensional state vector. Furthermore, once we have demonstrated the validity of our concepts using a one-dimensional vector, the problems of implementing future-state decisionmaking using a multidimensional state vector revolve around the development of credible prediction, valuation and decisionmaking algorithms, rather than proving the basic soundness of the concept.

A fundamental difference between our view of the state vector and current practice is that we view the state vector as a continually varying function of time, with not only a current value, but also a past history, and, even more important, a degree of future predictability. Almost all current models view the state (whether they refer to it by this name or not) as purely the current value(s) of the model attribute(s). To accent our view, we shall denote the state of the $i^{th}$ entity as:

$$\mathbf{s}^{(i)}(t) \quad ,$$

where the bold-facing indicates a (possibly) vector quantity. We again emphasize that the dimension and specific components of the state vector are open to choice - there is no stone tablet saying the state must be four-dimensional and consist of the number of weapon systems, effective personnel strength, amount of ammunition, and POL level.

## VI. Plans, Missions, Constraints

As discussed earlier, we believe the proper role of the current state, in both actual and model decisionmaking, is to act as a *trigger* for a planning process, by causing a conclusion that "things are not going well." But this view requires that the decisionmaker have an already formed or stated idea of what would be a desireable future, so that he or she could decide whether a specific action would "make things better." Or, more explicitly, future-state decisionmaking requires the existence of some form of *plan.*

There should be nothing startling about this observation with respect to combat modelling. According to doctrine, in an actual combat situation each level of command would be operating in conformance with an operation plan (OPLAN) or order (OPORD). This plan or order would follow the traditional five paragraph [14] format:

1. Situation
2. Mission
3. Execution
4. Service Support
5. Command and Signal

The situation paragraph contains both information on the friendly task organization, including conditions and times of attachments and detachments, and on the assumed enemy order of battle. The mission paragraph is usually a fairly general statement of the goals or objectives of the operation and the general methods that will be utilized to accomplish them, e.g. to conduct a defense in depth to destroy attacking first-echelon divisions forward of a certain line. The execution paragraph then follows with more specific tasks (missions) for subordinate units, and also with a description of a scheme of maneuver, which is in general a time-phased description of how the commander views the battle as evolving. Lastly (for our purposes), the service support paragraph contains information on logistical constraints, e.g. ammunition controlled supply rates (CSR's), etc.

We would assert that if a systemic model is to make realistic and believable decisions, based on a future-state decisionmaking model, then most of this same information (or model analogs of it) must be available within the model. We further assert that the nature of most "real-world" OPORDs and OPLANs dovetails exceptionally well with the demands of future-state model decisionmaking. Actual OPORD and OPLANs contain numerous time and distance-oriented control measures - phase lines, coordination points, release points, etc., that carry with them explicit or implicit assumptions about what the situation or scenario will be at that time. Furthermore, even many of the qualitative statements in an OPORD or OPLAN have quantitative interpretations (although military operations research experts are still arguing vehemently about the values used). For example, a Sovietstyle attacking force might be considered destroyed if attrited to forty percent of its full strength, while a US unit is frequently considered combat ineffective if it falls below seventy percent of TOE. (The actual numbers are not the issue - only that qualitative mission statements may be converted to reasonably credible quantitative measures. The actual procedure(s) by such conversions would occur is beyond the scope of this paper.)

The actual form and format of a model plan would be the choice of the modeler, just as are the components of the state vector. The only fundamental restrictions would seem to be that the model plan be time-sequenced, involve only quantitatively measurable entity attributes, and express desired results in terms of either minimum or maximum values of quantities derivable from those attributes. For example, a model plan might consist of

(1) A sequence of times - $t_i$ .

(2) For each $t_i$,

  (a) A mission during the time $t_i$ to $t_{i+1}$ .

  (b) Sector boundaries during the time $t_i$ to $t_{i+1}$ .

  (c) A desired FLOT trace at $t_i$ .

  (d) Planned friendly attachments/detachments at $t_i$ .

  (e) Anticipated new enemy units introduced at $t_i$ .

  (f) Minimum friendly unit states permissible at $t_i$ .

  (g) Maximum enemy unit states permissible at $t_i$ .

Again, this list is not necessarly either complete or exhaustive - only illustrative. The exact specification of what should be included in a model plan is best determined on a case by case basis.

## VII. Future State Prediction Algorithms

The ability to predict or visualize the manner in which a particular action or sequence of actions will affect the future is crucial to most planning. For example, in the U.S. Army Command and General Staff College's structured decisionmaking process called the *Estimate of the Situation* [15], this ability or process is referred to as *War Gaming* and is one of, if not the, key step by which a staff officer is supposed to develop the advantages and disadvantages of a tactical course of action. In the model decisionmaking arena, this ability translates into having within the model algorithms for predicting the future quantitative values of the state vector $\mathbf{s}(t)$. As we have alluded to before, herein lies what we feel is the fatal flaw in the present-state decisionmaking paradigm - in present-state decisionmaking these prediction algorithms, together with all their assumptions, exist only in the programmer or analyst's head and are therefore not subject to either examination or audit trail when the actual combat model is executed.

Many such quantitative algorithms in fact already exist and are in use in actual combat planning situations. Much of FM 101-10-1 [13] is nothing more than a collection of factors to perform exactly such computations. A similar comment holds for Lanchester equations. In the extreme, a combat model might even call itself to calculate the future resulting from a specific decision. (A similar procedure was adopted by some of the early computerized chess-playing programs. There are overwhelming practical reasons, however, while this idea should not be used in combat models.)

Before proceeding with this, however, there is a need, which we hope will become apparent shortly, to refine and expand our notation. The reason for this is that while we are viewing the evolution of the state vector as analagous to a trajectory in the ordinary differential equations sense, such a trajectory is uniquely determined based on a single set of initial conditions only if the actual model is both deterministic and completely known. In the combat modelling context, this would make the only allowable prediction algorithm the running of the model itself, and require both using "ground truth" for initial data and complete knowledge by each side of the other's plans and decisionmaking algorithms. Clearly this is too restrictive. We therefore need to distinguish between the actual state of an entity at a particular time and predicted values of that state at the same time. We further need to distinguish between the predicted values of the state of the same entity, but based on predictions made at different times, or under different assumptions, since these could easily be different.

We therefore introduce the following extension of the notation for the state vector

$$\mathrm{s}_p^{(i)}(t; \mathrm{S}(t_j), C_A)$$

which stands for the value of the state vector $\mathrm{s}^{(i)}(t)$, predicted at $t_j$ based on a perceived "state of the world" (denoted by $\mathrm{S}(t_j)$) and on an assumed course of action $C_A$. Note that the perceived state of the world and the assumed course of action are, at least to a degree, independent. For example, the future state of a battalion task force in the defense would clearly depend not only on its current perceived strength (state), but also on how its higher command anticipated using it, e.g. in an economy of force versus a terrain retention mission.

Note that based on this definition, it is quite possible for

$$\mathrm{s}_p^{(i)}(t; \mathrm{S}(t_j), C_A) \neq \mathrm{s}_p^{(i)}(t; \mathrm{S}(t_k), C_A) \quad , \quad t_j \neq t_k$$

due to changes in the perceived state of the world between $t_j$ and $t_k$, even though neither the actual state of the entity nor the course of action have changed. Furthermore, such could happen even if the perceived state of the world agrees with ground truth, because, assuming $t_j < t_k$, there is no guarantee that

$$\mathrm{s}^{(i)}(t_k) = \mathrm{s}_p^{(i)}(t_k; \mathrm{S}(t_j), C_A) \quad .$$

i.e. prediction does not have to be perfect. Lastly, as far as the prediction algorithms themselves are concerned, it is irrelevant as to whether the perceived state of the world used for prediction is ground truth or not - although such will clearly affect the *actual* values predicted by the algorithms.

Some of these ideas are ilustrated by the different trajectories in Figure 1.

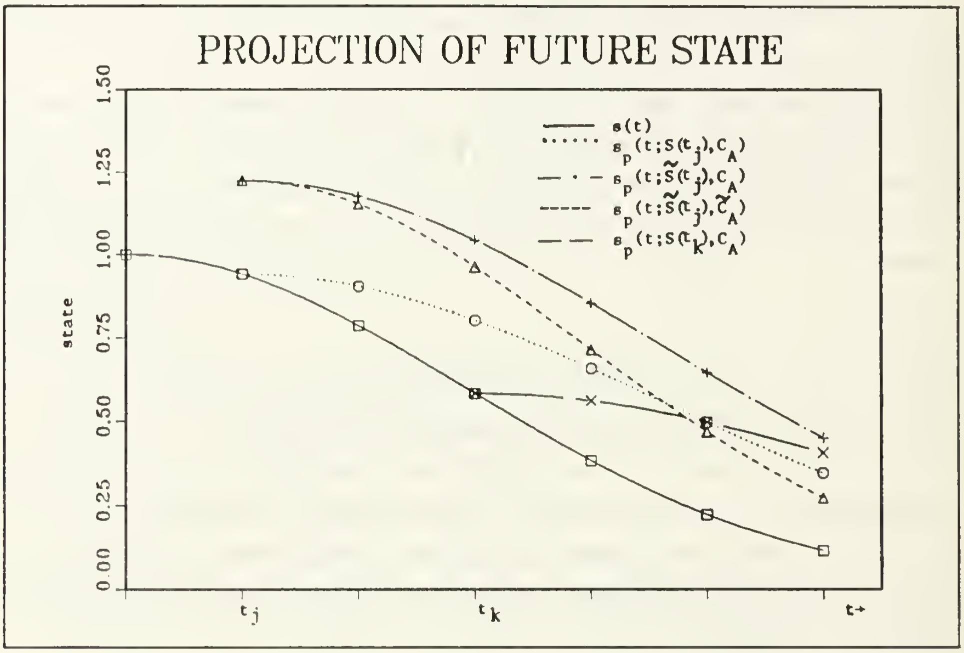


Figure 1

In this figure, the state is one-dimensional and only a single entity is being considered, so the superscript $(i)$ is not shown. The actual state is shown by the curve s(t). The curves $s_p(t; S(t_j), C_A)$ and $s_p(t; S(t_k), C_A)$ illustrate how the predicted future state may change, based on when the prediction is made, even though ground truth is used and the plan has not changed. (The reason of course, is that the future did not evolve exactly as predicted during the time $t_j < t < t_k$.) The curves $s_p(t; \tilde{S}(t_j), C_A)$ and $s_p(t; \tilde{S}(t_j), \tilde{C}_A)$ illustrate both how an incorrect perception of the state of the world (i.e. lack of ground truth) and different courses of action may lead to different predictions, even at $t = t_j$ itself.

As with deciding what are the appropriate components of the state vector, the determination of specific prediction algorithms should be decided on a case-by-case, model-by-model basis. Furthermore, the same basic type of algorithm does not need to be used for each attribute. For example, FM 101-10-1 [13] data might be used to predict POL levels, while Lanchester equations might be used to predict attrition. We would anticipate that negative exponentials would figure frequently in these algorithms however, both because of their ease of evaluation and because of the fact that they correspond to constant percentage changes per unit of time.

## VIII. The Power or Value of an Entity

Previous sections have addressed the question of computing either the present or future state of an entity. However, in actual operations, knowledge of the state of the entities on the battlefield alone is not sufficient for military planning. There is also a requirement for a single consistent measure of military utility which can describe the potential effectiveness of any entity or unit on the battlefield. The most commonly used term for this measure in the military literature is *combat power* [3]. As indicated in our preliminary discussion, an integral part of the GVS model architecture is the existence of model algorithms that can compute such a quantitative measure for each model entity, given the state of that entity. (The choice of the word used here is to some degree, semantic. We shall use the term power for the remainder of this paper. However, the reader who feels more comfortable with either the term value or combat power is welcome to use that interpretation.)

Mathematically, such algorithms are simply transformations from a (generally) multi-dimensional (state) space to a single (power) dimension. That such algorithms are both necessary and appopriate can be argued from both model and "real-world" considerations. Given today's state of the modeling art, it seems unlikely that models in the forseeable future will be able to implement decision logic other than either "IF ... THEN" trees (TDR's) or optimization of a single quantative figure of merit (objective function) among competing options. Furthermore, today's interest in computer-assisted multiattribute decisionmaking methods [5] strongly argues that human decisionmakers are more comfortable in general when a multidimensional decision has been projected down to a single point on a one-dimensional scale.

The scale used to measure power must, of course, be only relative. What is crucial, especially for higher-level decisionmaking, is that the methodology be able to produce a measure which is consistent over the wide diversity of entities and units on the Airland battlefield. This last consideration was the major reason for our earlier introduction of a much more limited version of the Generalized Value System [10] designed to produce a measure of value for weapon allocation decisions. As we have already commented, this idea was extended by Kilmer [7] to encompass force allocation decisions as well. We shall use much of his terminology in the subsequent discussion.

We feel that the development of a consistent system for the measure of power or value on the Airland battlefield must start with three fundamental premises. These premises recognize that, at the operational level, power must measure not only the power of combat forces but also the contribution of combat support and combat service support forces. Furthermore, the measure must recognize the effects not only of forces in contact or in position to fire or otherwise perform their mission.

but also the *potential* power of forces (such as reserves and follow-on forces) that are not in contact or position at the present, but may be *at some time in the future.* The three premises, which were originally introduced in [10], and have been slightly rephrased below, are:

> The only entities with inherent power are maneuver and fire support.
>
> Combat support and combat service support entities derive power from the increase in the power of the maneuver and fire support units they support.
>
> The power of entities which are not in position to perform their combat mission is a *discounted* value of the power they would have when in position. The discounting factor is determined by the *time interval* before they will be in position, ready to perform their combat mission.

In the GVS architecture, the starting point for determining power or value is the determination of a *power function* which yields a numerical value for the power of an entity, given the state of the entity at that time, assuming the entity is in position to perform its combat mission. The choice of this power function, which we shall denote:

$$P(\mathsf{s}(t)) \quad ,$$

where $\mathsf{s}(t)$ is the state of the entity at time $t$, is up to the model developer or analyst. In tests of these concepts which were implemented using the VIC model [11], we used the VIC *mass* function and evaluated only maneuver units. Firepower scores could also be used if desired. We would emphasize here, and this is crucial to the understanding of GVS, that the purpose of this power function is not to determine the "winner" of the battle. The purpose is solely to simulate that portion of the doctrinal decisionmaking process [15] where the planner decides whether he or she has enough assets to "do the job." This is a far less restrictive criterion than determining battle outcome. Therefore any power function which produces "reasonable" values for relative combat power would be acceptable.

One drawback, however, of using either firepower scores or the VIC mass function as the power function in a fully mature Airland Battle model is that the former two are essentially based on a one-dimensional state vector. A recent exciting result in this area is a thesis by Crawford [2]. This thesis describes an experimental methodology for determining a multidimensional mapping for the power function ($P(\mathsf{s}(t))$). The objective of this thesis was to determine the relative importance, in terms of contribution to perceived combat power, of various system state ($\mathsf{s}(t)$) attributes to a decisionmaker's estimate of his unit's ability to accomplish its assigned mission ($C_A$). A four-dimensional state vector, encompassing personnel, vechicles, ammunition and POL was considered. The Categorical Judgement Method [8] was used to analyze responses from sixty "judges" - all Army officers with field experience, to 144 combinations of state vector values. (A sample of the questionaire and response form used is at Appendix A.) Using contour surface plot analysis, an explicit formula (in terms of ellipsoids) was determined by least squares (regression) methods. The formula had a coefficient of determination ($r^2$) of 84% and a standard deviation ($\sigma$) of 6.41, indicating an excellent consensus among the "decisionmakers." We feel this study demonstrates the feasibility of developing credible power function mappings, based on military judgement, for the more general multidimensional states necessary to fully describe all entities on the Airland battlefield. (As an aside, we are also optimistic that Crawford's methodology has significant potential to be incorporated into a decision aid for combat unit staff planners.)

Several of the various power representations introduced by Kilmer [7] can be shown to be, in fact, special cases of this general power function. For example, if

$$\tilde{\mathrm{s}}_0(t)$$

denotes a combat unit whose state is 100% of authorized levels in all measured attributes, then Kilmer's Basic Inherent Power (BIP) is simply

$$P(\tilde{\mathrm{s}}_0(t)) \qquad ,$$

provided the unit is in position and conducting its primary mission against its most likely threat. The two factors which will then cause an entity to be at other than its BIP are

1. The unit is not at full authorized (TOE) levels, or
2. The unit is not in position to perform its mission, or both.

For combat units which are in position, but not at full authorized levels, the power function

$$P(\mathrm{s}(t))$$

produces the value which Kilmer called the Adjusted Basic Inherent Power (ABIP). Furthermore, given the future state prediction algorithm described in Section VII, the power function evaluated at the predicted future state of a combat entity in contact at that time, i.e.

$$P(\mathrm{s}_p(t; \mathrm{S}(t_j), C_A))$$

becomes what Kilmer defines as the Predicted Adjusted Basic Inherent Power (PABIP) of that unit.

In the GVS, unit power is degraded if the unit is not in position or available to perform its mission at a given time. A major element of the GVS is computation of this degradation by regarding a unit which, at time $t$, will not be in position to perform its mission until time $t_A$, as analagous to financial assets which mature at $t_A$. That is, its power at time $t$ is *discounted* from its power (PABIP), depending on $(t - t_A)$. This approach has the advantages both that discounting of future assets is a well-recognized procedure and that normal (i.e. by a fixed percentage) discounting corresponds to *exponential decay* of value.

Thus, Kilmer's Situationally Inherent Power (SIP) at some time $t$ is in fact

$$P(\mathbf{s}_p(t; \mathbf{S}(t_j), C_A))e^{-D(t_A - t)} \qquad ,$$

where $D$ is chosen so that entities which are more than some prescribed time interval from being in position have only negligible amounts of power. These predicted future values of the SIP form the basis under the GVS methodology for making decisions on courses of action.

## IX. GVS-Based Decision-making

As outlined above, the final element of the GVS architecture involves the use of the computed current and future values, together with whatever plans, missions or constraints exist, to arrive at decisions. We feel that a great deal of additional research will be required in this area to identify the most suitable algorithms. Furthermore, since the GVS is an architecture rather than a rigid set of prescribed formulas, it is quite possible that multiple acceptable alternative decisionmaking algorithms will emerge, depending on the particular model considered. The fundamental requirements are first that the algorithms must all consider the projected future states, not only the present state. Secondly, they must produce a clearly understandable audit trail. Thirdly, a certain time interval, called the *planning horizon*, must be specified. At any time when a decision is being considered, the prediction algorithms must first be invoked to extrapolate the current state out to the planning horizon. Lastly, based on the SIP's computed, as well as the mission and constraints specified, an evaluation must be made as to whether or not the predicted future state conforms to the plan. If so, no decision need be made. If not, another algorithm must then be invoked to determine how to restore conformity to the plan at tha time.

In this section we present an example, taken from Crawford [2], of GVS-based decisionmaking. The example is minimal in that only a single option (other than no change) is considered, although later papers will discuss the situation of multiple options.

In this example, a heterogeneous Blue force is defending against a heterogeneous attacking Red force. Both forces are initially at full strength, with the Red force located 16,200 meters from the Blue force and advancing at a rate of 270 meters per minute. We further assume that the Blue force has a BIP (full TOE) of 1000 units when defending, and the Red force a BIP of 2000 while attacking. The

Blue mission will be to retain a superiority of power at the FLOT, and the Blue planning horizon is assumed to be sixty minutes. The Red force is assumed to be able to fire effective artillery preparation at a range of approximately 8,000 meters (or in about thirty minutes). We consider this to be the position when they are in contact. The constant $D$ is chosen so that Red forces thirty minutes from contact have a situationally adjusted power of only 5% of their BIP, i.e.

$$e^{-30D} = 0.05 , \implies D = 0.0998/\text{minute} \qquad .$$

(We would comment that the thirty minute figure was chosen by Crawford, and is probably unreasonably low.)

The state vector for each force consists of four elements - personnel, ammunition, POL, and vehicles. The forces are assumed to be subject to attrition at two different rates - one during the period $t = 0$ to $t = 30$, the second during $t = 30$ to $t = 60$ (after contact is made). The rates used are shown in Table 1. These rates are abitrarily assigned, but reflect the idea that during the time from $t = 0$ until $t = 30$, the losses on both sides are due mainly to harassing artillery fire plus Red vehicle breakdown, while after $t = 30$ the losses increase due to artillery preparation and the direct fire battle. This table becomes the effective future state prediction algorithm. Based on the predicted attrited states, Crawford's fitted power function ($DPF$) [2] is used to produce predicted powers. The predicted powers out to $t = 60$ are shown in Figure 2.

**Table 1. BLUE AND RED FORCES ATTRITION RATES PER MINUTE**

| Time (Min) | Blue Forces | | | | Red Forces | | | |
|---|---|---|---|---|---|---|---|---|
| | PER | AMMO | VEH | POL | PER | AMMO | VEH | POL |
| 0 - 30 | 0.333 | 0.500 | 0.000 | 0.333 | 0.167 | 0.067 | 0.067 | 0.333 |
| 30 - 60 | 1.333 | 1.500 | 1.333 | 0.333 | 1.700 | 2.433 | 1.800 | 0.333 |

The following notation will be used:

$$\mathbf{s}^B(t) = \text{Blue State vector}$$
$$\mathbf{s}^R(t) = \text{Red State vector}$$
$$t_p = \text{Present time in the example } (= 0)$$
$$t_e = \text{Length of planning horizon } (= 60\text{min})$$
$$t_A = \text{Time until Red Force is in position } (= 30 \text{ min})$$
$$D = \text{Discounting constant}$$

The following then hold:

$$
\begin{aligned}
P(\mathrm{s}^B(t_p)) &\equiv \mathrm{BIP}^B = 1000 \\
P(\mathrm{s}^R(t_p)) &\equiv \mathrm{BIP}^R = 2000 \\
P(\mathbf{s}_p^B(t; \mathrm{S}^B(t_p), C_A)) &\equiv PABIP^B = 1000 * DPF(\mathbf{s}_p^B(t; \mathrm{S}(t_p), C_A)) \\
P(\mathbf{s}_p^R(t; \mathrm{S}^R(t_p), C_A)) &\equiv PABIP^R = 2000 * DPF(\mathbf{s}_p^R(t; \mathrm{S}(t_p), C_A)) \\
SIP^B &= PABIP^B \\
SIP^R &\equiv \begin{cases} PABIP^R \ e^{-D(t_A - t)} & , t_p < t < t_A \\ PABIP^R & , t_A \leq t \end{cases}
\end{aligned}
$$

(Note that since the Blue force is initially in position, and since the decisionmaking is made from the Blue point of view, the Blue SIP is never discounted.)

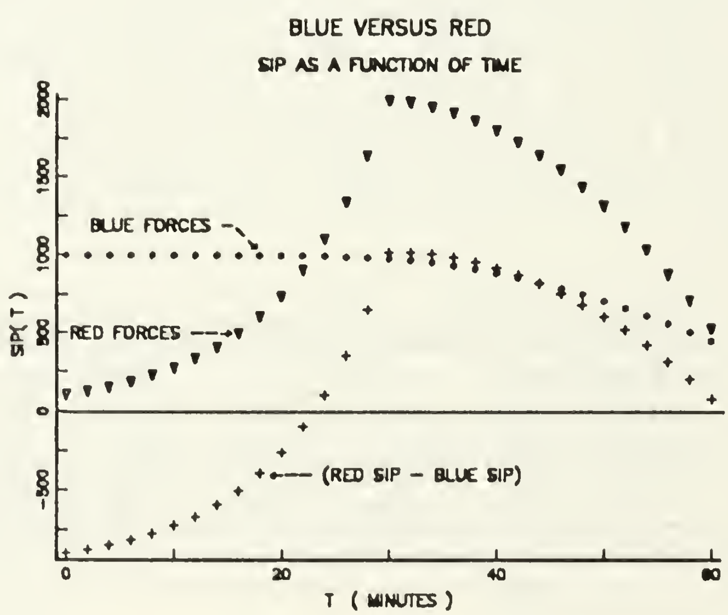


Figure 2 Predicted Blue Versus Red Battle

The predicted computed power curves for this example are shown in Figure 2. Note as the Red force moves into its attack position, its SIP increases, but with some degradation due to the attrition effects on the state vector. Once the Red force commences the attack, the attrition rate increases and their SIP (which is no longer discounted since they are now in contact) reduces correspondingly due to the losses. As the attacker, we expect their power to erode relatively faster than that of the defender. Even so, in this figure, because of Red's initial greater basic power (BIP), the attrition algorithm predicts that by $t = 60$ the Red force's SIP will equal **Blue force**'s, and therefore the Blue commander will not have met his constraint.

However, because the Blue commander predicts *at* $t = 0$ that by $t = 60$ he will not be able to accomplish his mission, he will have to plan some action to alter the predicted future. For example, he may request reinforcements, which must then arrive before $t = 60$. The predicted power curves for such a course of action are displayed in Figure 3. In this figure, the same basic powers, movement rates and attritions were assumed for the initial Blue and Red forces, and the reinforcements were assumed to have a BIP of 1000 and to arrive at $t = 30$. As the figure shows, the Blue force is now able to meet the mission of retaining a superiority of (combat) power over Red.

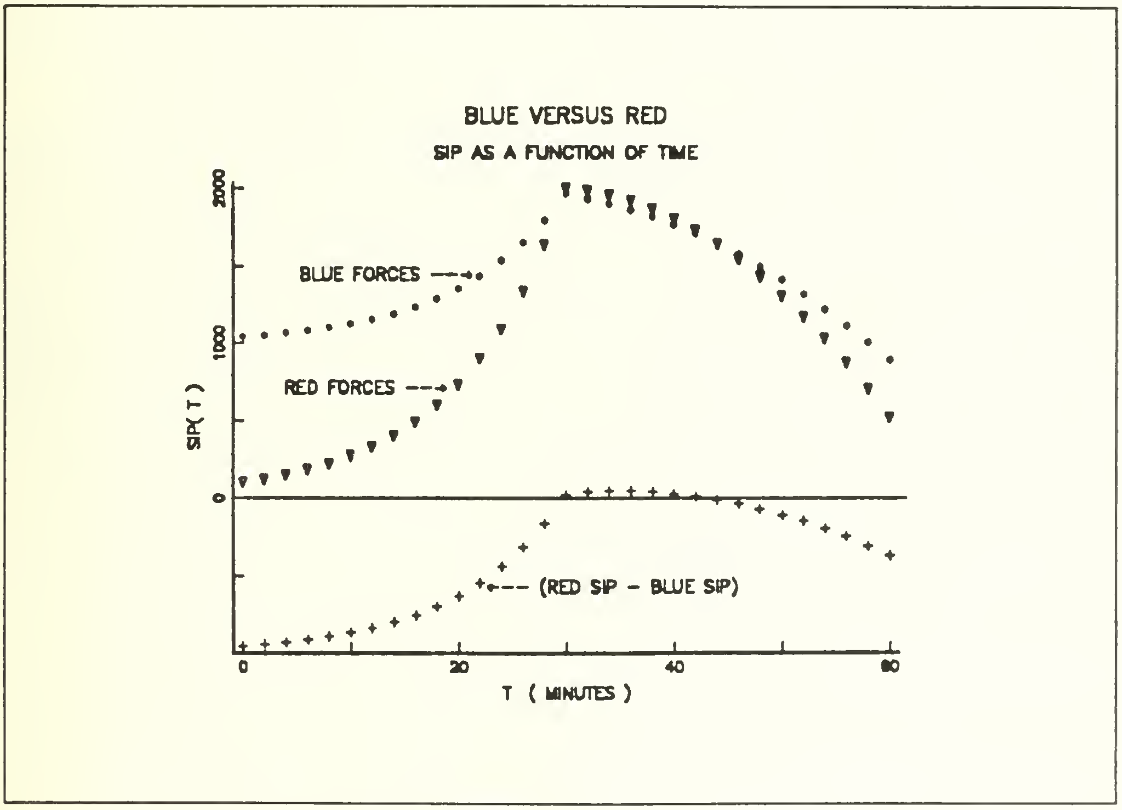


Figure 3 Predicted Blue Versus Red Battle With Blue Reinforcements

While this example is extremely artificial, it nevertheless illustrates the fundamental element of the GVS decisionmaking architecture. Future state forecasting is the only way the Blue force commander can decide *at* $t = 0$ to *initiate commitment* of a reserve so as to *realize success* at $t = 60$. Decision tables based on the state at $t = 0$ would almost never capture this, without significant "hard-wiring." Furthermore, if, after the actual execution model of the battle were run, Blue did not in fact accomplish his assigned mission, the GVS architecture would allow an analyst to determine exactly where and why the actual evolved state(s) differed from the prediction, and decide whether a "fix" needs to be implemented - e.g. the attrition rates used may have been incorrect.

## I. Summary and Conclusions

This report has examined what we believe is a fundamental flaw in current systemic combat models - the present-state decisionmaking paradigm. We believe this paradigm is basically flawed because it is not realistic (except perhaps at the platoon level and below) and because it relies on hidden models. We have also proposed what we believe is a viable alternative - the future-state decisionmaking architecture of the Generalized Value System [GVS]. We believe we have shown that this architecture is more realistic than present-state decisionmaking, that it is practical to implement, and that it is the only currently available alternative to present-state decisionmaking.

As we have outlined it here, the GVS architecture requires five elements - a defined state vector; explicit algorithms for predicting that state into the future; algorithms for converting state into a one-dimensional measure of power; a plan against which future states and powers can be compared; and lastly algorithms for making decisions based on the plan and projected future powers. There is still a great deal more research remaining to be done on this architecture, especially on decision algorithms for this paradigm. However, based on preliminary results to date, we are highly optimistic that the GVS architecture offers the promise of a significant qualitative improvement in higher-level systemic combat models.

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# APPENDIX A. SAMPLE QUESTIONAIRE

## A. PURPOSE & MOTIVATION

The purpose of this questionaire is to obtain an estimate of the degradation in a units effectiveness based on the threat posed, by the degradation in the 4 key variables of a unit. This questionaire will not just be used as a subject for a thesis and later diregarded. It is to be used to help the S-3 and decision maker to determine if he can handle a mission based on 4 key factors. Your answers are therefore very important to insure a good decision is made. You answers, as the decision maker, of the percent degradation of your units effectiveness based on the changes to these key variables is a measure of the relative importance of each variable to the accomplishment of your mission. Your answers will also help to develop a more accurate and realistic representation of how changes to the key variables effect your view of its relative importance.

### 1. Key Variables

The 4 key variables used throughout this questionaire are:

% Personnel,

% Ammo,

% Weapon Systems / Combat Vehicles, and

% POL (Fuel) .

### 2. Instructions

In the remainder of this questionaire, you will be asked to place yourself in the role of the decision maker of the unit and determine how changes to your units fuel, ammo, personnel and vehicles will effect your interpretation of your units ability to accomplish its assigned mission.

Please respond to the questions asked in accordance with your feelings regarding the situation. There is no right or wrong answer to any of the questions. As a decision maker in a combat situation you will be required to make rapid estimates of the situation. Therefore, with this in mind you should only take enough time to fully understand the situation presented and record your response. Once you have recorded a response you should not change your response.

You will receive an example question and two practice questions. You are then asked to answer 48 questions by putting an X under the response you feel best describes the unit's ability to accomplish its assigned mission.

Based on the following situation you will be asked to answer questions on the degree to which you determine your unit is able to accomplish its assigned mission. Use the following situation to answer all of the questions in this survey.

**Situation**

1. Enemy - 127th Motorized Rifle Regiment.

2. Friendly - Your unit 2nd Bn 41st Inf Mech is currently conducting deliberate defensive operations along the forward line of troops (FLOT).
   - Your unit is presently in prepared defensive positions.
   - Your unit is the forward unit. i.e. no units to your front.
   - Your unit is currently engaged in combat with the enemy.

**Mission**

Your unit 2/41st Inf (M) will conduct a deliberate defense of present positions for a minimum of 24 hours, longer if possible, to prevent the enemy from controlling this key terrain.

Based on the above scenario and mission answer the following questions.

## B. EXAMPLE OF THE RESPONSE FORM

*****************************************************************************

THE CURRENT STATUS OF YOUR UNIT IS :

75% PERSONNEL,

25% AMMUNITION,

50% WEAPON SYSTEMS, and

50% POL (FUEL) .

BASED ON THIS STATUS, INDICATE BELOW THE CURRENT EFFECTIVENESS OF YOUR UNIT'S ABILITY TO CONTINUE TO ACCOMPLISH ITS CURRENT MISSION OF DELIBERATE DEFENSE.

| TOTALLY EFFECTIVE | EFFECTIVE | MARGINAL | INEFFECTIVE | TOTALLY INEFFECTIVE |
|---|---|---|---|---|
| ( ) | ( ) | ( ) | ( ) | ( ) |

*****************************************************************************

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